

Systematic study for particle transverse momentum asymmetry in minimum bias pp collisions at LHC energies

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In PYTHIA6 (PYTHIA8) once the transverse momentum p_T of a generated particle is randomly sampled, p_x and p_y are set on the circle with radius of p_T randomly. This may largely suppress the development of the final hadronic state transverse momentum anisotropy from the initial state spatial asymmetry. We modify PYTHIA6.4 by randomly setting p_x and p_y on the circumference of an ellipse with the half major and minor axes being $p_T(1 + \delta_p)$ and $p_T(1 - \delta_p)$, respectively. The modified PYTHIA6.4 is then employed to systematically study the charged particle transverse momentum asymmetry in the minimum bias pp collisions at $\sqrt{s}=0.9, 7$, and 14 TeV. The ALICE data on the transverse sphericity as a function of charged multiplicity, $\langle S_T \rangle(N_{ch})$, are well reproduced with the modified PYTHIA6.4. It is found that the predicted charged particle v_2 upper limit is a measurable value, ~ 0.12 , in the minimum bias pp collisions at $\sqrt{s}=7$ TeV. We suggest a systematic measurement for the particle transverse momentum sphericity, eccentricity (ellipticity), and elliptic flow parameter.

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The event shapes are relevant to the properties of hadronic final state. One has employed the hadronic event shape measurements to test asymptotic freedom and to extract the strong coupling constant, etc. in the e^+e^- annihilation and lepton deep inelastic scattering, respectively, for a long time [1, 2]. Recently, the final hadronic event shapes in pp collisions at LHC energies have been measured by CMS [3], ALICE [4, 5], and ATLAS [6, 7].

In order to avoid bias from the boost along beam axis [8], this study is restricted to the transverse momentum plane. We start from the transverse momentum matrix

of produced charged particles [5]

$$\mathbf{S}_{\mathbf{xy}} = \frac{1}{\sum_i p_{T_i}} \sum_i \frac{1}{p_{T_i}} \begin{pmatrix} p_{x_i}^2 & p_{x_i} p_{y_i} \\ p_{y_i} p_{x_i} & p_{y_i}^2 \end{pmatrix}, \quad (1)$$

where p_{T_i} is the transverse momentum of particle i , p_{x_i} and p_{y_i} are the transverse momentum components, and the sum here runs over the charged particles in a single event. The two eigenvalues of this transverse momentum matrix satisfy $\lambda_1 + \lambda_2 = 1$. If the two roots are ordered in $\lambda_1 > \lambda_2$, the transverse momentum sphericity is then defined as [5]

$$S_T = 2\lambda_2. \quad (2)$$

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By intuitive construction one knows that S_T possesses

limits of

$$S_T = \begin{cases} 0, & \text{pencil-like limit} \\ 1, & \text{isotropic limit} \end{cases} \quad (3)$$

The event averaged transverse momentum sphericity is then denoted as $\langle S_T \rangle$, where $\langle \dots \rangle$ indicates an average over events.

The dimensionless observable

$$\epsilon_p = \frac{\sum_i [p_{x_i}^2 - p_{y_i}^2]}{\sum_i [p_{x_i}^2 + p_{y_i}^2]} \quad (4)$$

with limits of

$$\epsilon_p = \begin{cases} 1, & \text{pencil-like limit} \\ 0, & \text{isotropic limit} \end{cases} \quad (5)$$

was first introduced in [9] to investigate the particle transverse momentum asymmetry. We are inspired by [10] to identify this observable as transverse momentum eccentricity (ellipticity). According to the limits in Eqs. (3) and (5) one may intuitively assume that S_T is inversely proportional to ϵ_p , that is, a larger sphericity corresponds to a smaller ellipticity (eccentricity) and vice versa. Then the event averaged transverse momentum eccentricity (ellipticity) is

$$\langle \epsilon_p \rangle = \left\langle \frac{\sum_i [p_{x_i}^2 - p_{y_i}^2]}{\sum_i [p_{x_i}^2 + p_{y_i}^2]} \right\rangle. \quad (6)$$

Unfortunately, the transverse momentum eccentricity (ellipticity) was no longer a hot topic since then.

The particle transverse momentum asymmetry was also proposed to be studied by the harmonic coefficients in the Fourier expansion of particle transverse momentum azimuthal distribution [11, 12]. The second harmonic coefficient (elliptic flow parameter v_2) is specially important because the large v_2 of emitted particles is a characteristic feature of the hot and dense medium created in the ultra-relativistic nuclear collisions. It has contributed to the suggestion of a strongly coupled quark-gluon plasma (sQGP) observed in the nucleus-nucleus collisions at RHIC energies [13–16]. This elliptic flow parameter v_2 is expressed [12] as

$$\langle v_2 \rangle_p = \langle \cos[2(\phi - \Psi_r)] \rangle_p = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle_p, \quad (7)$$

where ϕ refers to the azimuthal angle of particle transverse momentum, Ψ_r stands for the reaction plane angle, and $\langle \dots \rangle_p$ denotes an average over all particles in all events, which is a particle-wise average [17]. As mentioned in [17], in order to take the multiplicity effect into account it is better to employ the event-wise average v_2 expressed as

$$\langle v_2 \rangle_e = \langle \cos[2(\phi - \Psi_r)] \rangle_e = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle_e \quad (8)$$

where $\langle \dots \rangle_e$ indicates an average first over particles in a single event and then over events. Note that the event-wise averaged $\langle v_2 \rangle_e$ is different from the $\langle \epsilon_p \rangle$ in Eq. (6).

As mentioned in [6] that the charged particle transverse momentum sphericity is measured (defined) “using jets to represent the final state four-momentum.” As the same elemental observables, p_{x_i} and p_{y_i} , appear in Eq. (1) and (4), the simultaneous measurement of sphericity and ellipticity (eccentricity) is not hard. This measurement is only effected by the jet reconstruction. However, the measurement of v_2 , whatever the event plane method [12] or the Lee-Yang zero point method [18] or the cumulant method [19], is more model dependent, such as the decomposition of the nonflow [20] etc. The cumulant method is further identified with two-, four-, and six-particle cumulants. The discrepancy among the measured v_2 with different methods may reach 10-100% [21, 22]. Recently, one even argued that the event plane method is obsolete [23]. Therefore, we strongly suggest that the transverse momentum sphericity, ellipticity (eccentricity), and the elliptic flow parameter should be measured simultaneously, for the benefit of cross checking and reliable measurements.

The ALICE data of charged particle transverse sphericity have been simulated with the different PYTHIA6 tunes [5] and are best reproduced by the PERUGIA-2011 tune [24]. In the PERUGIA-2011 tune a number of theoretical parameters, relevant to the soft- and hard- processes as well as the parton distribution function etc., are fitted to the data taken in hadronic Z^0

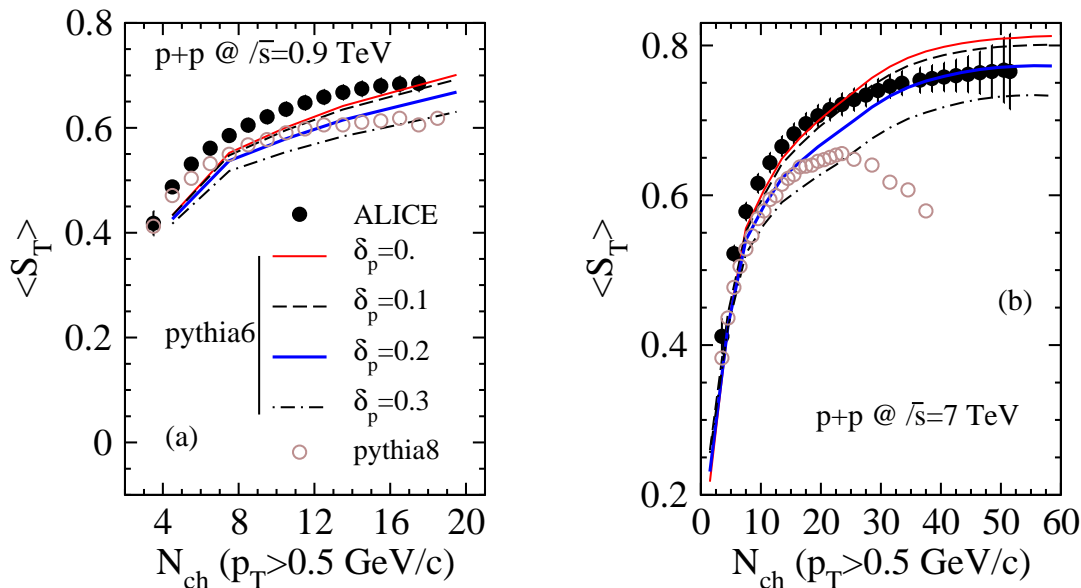


FIG. 1: (colour on line) Charged particle event averaged transverse sphericity as a function of charged multiplicity in the minimum bias pp collisions at (a) $\sqrt{s}=0.9$ TeV and (b) $\sqrt{s}=7$ TeV. The ALICE data are taken from [5] and the PYTHIA8 results are copied from [5].

decay at LEP, to the Tevatron min-bias data at different energies, to the Tevatron Drell-Yan data, and to the SPS min-bias data, etc. Therefore, it is possible that one parameter fitted to the hadronic Z^0 decay data, for instance, is good for pion production in nuclear collisions but not suitable for kaon production. The physics in PYTHIA6 for kaon production may even be biased. This situation, of course, may exist in other PYTHIA6 tunes quoted in [5]. This causes that the different PYTHIA6 tunes have different potentials describing a single observable and that a single PYTHIA6 tune has different potentials describing the different physics. It is also the reason that why the PERUGIA-2011 tune can be used with only PYTHIA6 but not with PYTHIA8 [24]. Thus we prefer that the studied physics can be described by as simple modifications as possible to the existing model and/or by fitting as few model parameters as possible to the experimental data taken from the same reaction.

In PYTHIA6 (PYTHIA8) once the transverse momentum p_T of a generated particle is randomly sampled, p_x and p_y are then set on the circle with radius of p_T ran-

domly. This strongly cancels the final hadronic state transverse momentum anisotropy developed from the initial state spatial asymmetry. Therefore in this paper we modify PYTHIA6 (PYTHIA6.4 [25]) by randomly setting p_x and p_y on the circumference of an ellipse with the half major and minor axes being $p_T(1 + \delta_p)$ and $p_T(1 - \delta_p)$, respectively. This change is also introduced in the particle/parton production process of hard scattering, multiple interactions, initial- and final-state parton showers, as well as the adding of remnants [25]. Consequently, we re-calculate the $p_T = \sqrt{p_x^2 + p_y^2}$ and modify the transverse momentum distribution of final hadronic states. It turned out that, provided $\delta_p < 0.1$ (a small perturbation) the change in the transverse momentum distribution is weak, so the comparison of transverse momentum distribution with experimental data may not be effected.

The modified PYTHIA6.4 is then employed to simultaneously calculate the charged particle transverse sphericity, ellipticity (eccentricity), and elliptic flow parameter in the minimum bias pp collisions at $\sqrt{s}=0.9$,

7, and 14 TeV. In the calculations the model parameters are default [25] and the deformation parameter δ_p introduced in this work is first assumed to be 0, 0.1, 0.2, and 0.3, and then determined by fitting to the ALICE data on the event averaged charged particle transverse sphericity as a function of charged multiplicity, $\langle S_T \rangle(N_{ch})$ [5]. Note that the model reduces to the default PYTHIA6.4 [25] when $\delta_p=0$.

The calculated event averaged charged particle transverse sphericity as a function of charged multiplicity, $\langle S_T \rangle(N_{ch})$, is compared with the ALICE data [5] in Fig. 1 (a) and (b) for the minimum bias pp collisions at $\sqrt{s}=0.9$ and 7 TeV, respectively. In the figure the solid circles are the ALICE data of “all” events taken from [5]. The red solid, green dashed, blue thick solid, and black dash-dotted curves are calculated by the modified PYTHIA6.4 with $\delta_p=0, 0.1, 0.2$, and 0.3 , respectively. One sees in Fig. 1 (a) that the simulations reproduce the 0.9 TeV ALICE data with $\delta_p=0$ and 0.1 . We also see in this panel that PYTHIA8 is not so well comparing with the ALICE data, because it is not modified yet. Figure 1 (b) shows that the ALICE data of $\langle S_T \rangle(N_{ch})$ in the minimum bias pp collisions at $\sqrt{s}=7$ TeV are better reproduced by the simulations with $\delta_p=0.1$. The calculated charged particle v_2 upper limit is a measurable value of 0.119 (see Table I below).

Table I gives the event averaged charged particle transverse sphericity, eccentricity (ellipticity), and the elliptic flow parameter in the minimum bias pp collisions at $\sqrt{s}=0.9$ and 7 TeV. One sees in this table that:

- The event averaged charged particle transverse sphericity decreases with increasing deformation parameter δ_p but the event averaged charge particle eccentricity (ellipticity) and the v_2 upper limit (v_2^{up} in the table) behave quite the opposite. Therefore, the above assumption that S_T is inversely proportional to ϵ_p (v_2) is proved qualitatively. We have to mention here that the v_2 upper limit is calculated at the peak of the event-wise

averaged $v_2(p_T)$ in $|\eta| < 0.8$.

- The ALICE datum of event averaged charged particle transverse sphericity in the minimum bias pp collision at $\sqrt{s}=0.9$ TeV is reproduced the best with $\delta_p=0$, consistent with Fig. 1 (a). Then the charged particle v_2 upper limit is zero.
- It appears that for the pp collision at $\sqrt{s}=7$ TeV the ALICE datum of event averaged charged particle transverse sphericity, $\langle S_T \rangle_{exp}$, can be reproduced with δ_p from 0 to 0.2.

As shown in Table I, the calculated $\langle S_T \rangle_{the}$ is not so sensitive to δ_p , unlike $\langle \epsilon_p \rangle$ and v_2^{up} . $\langle S_T \rangle_{the}$ is also less sensitive to δ_p than the charged particle event averaged transverse sphericity as a function of charged multiplicity $\langle S_T \rangle(N_{ch})$ in Fig. 1 (b), since the former is obtained by averaging the later over N_{ch} . However, considering Table I together with Fig. 1 (b) it is reasonable to choose $\delta_p=0.1$. So the charged particle v_2 upper limit is a measurable value of 0.119, consistent with the existed prediction of 0.04 - 0.2 obtained by artificially setting parameters in the models to upper limits for the pp collisions at $\sqrt{s}=7$ and/or 14 TeV [26–28].

We then use $\delta_p=0.1$ to predict the charged particle event-wise averaged $v_2(\eta)$ ($0.5 < p_T < 20$ GeV/c) and $v_2(p_T)$ ($|\eta| < 0.8$) in the minimum bias pp collisions at $\sqrt{s}=7$ and 14 TeV as shown in Fig. 2 (a) and (b), respectively. We see in Fig. 2 that the charged particle v_2 upper limit estimated at the peak of the $v_2(p_T)$ in Fig. 2 (b) is larger than the one estimated at the peak of $v_2(\eta)$ in Fig. 2 (a), because the former is counted in a η interval of 1.6 but the later in an interval of 1. The v_2 upper limits, read at the peak of solid curve (for the pp collisions at $\sqrt{s}=14$ TeV) and the dashed curve (for the pp collisions at $\sqrt{s}=7$ TeV) in Fig. 2 (b), are 0.194 and 0.119, respectively. This is consistent with the existed predictions of 0.04 - 0.2 [26–28].

In summary, we have modified PYTHIA6.4 by setting the generated particles on the circumference of an

TABLE I: Event averaged charged particle transverse sphericity, eccentricity (ellipticity), and v_2 upper limit calculated at the peak of the event-wise averaged $v_2(p_T)$ ($|\eta| < 0.8$) in the minimum bias pp collisions at $\sqrt{s}=0.9$ TeV and $\sqrt{s}=7$ TeV.

$\sqrt{s}=0.9$ TeV					$\sqrt{s}=7$ TeV			
δ_p	$\langle S_T \rangle_{exp}^\dagger$	$\langle S_T \rangle_{the}$	$\langle \epsilon_p \rangle$	v_2^{up}	$\langle S_T \rangle_{exp}$	$\langle S_T \rangle_{the}$	$\langle \epsilon_p \rangle$	v_2^{up}
0.	0.613 \pm 0.020	0.602	0.000	0.000	0.700 \pm 0.048	0.703	0.000	0.000
0.1		0.597	0.109	0.105		0.696	0.109	0.119
0.2		0.582	0.215	0.207		0.672	0.213	0.237
0.3		0.555	0.315	0.302		0.632	0.310	0.347

† obtained by averaging the ALICE data in Fig. 1 (a) over N_{ch} and by quadratically summing the error bars in the ALICE data.

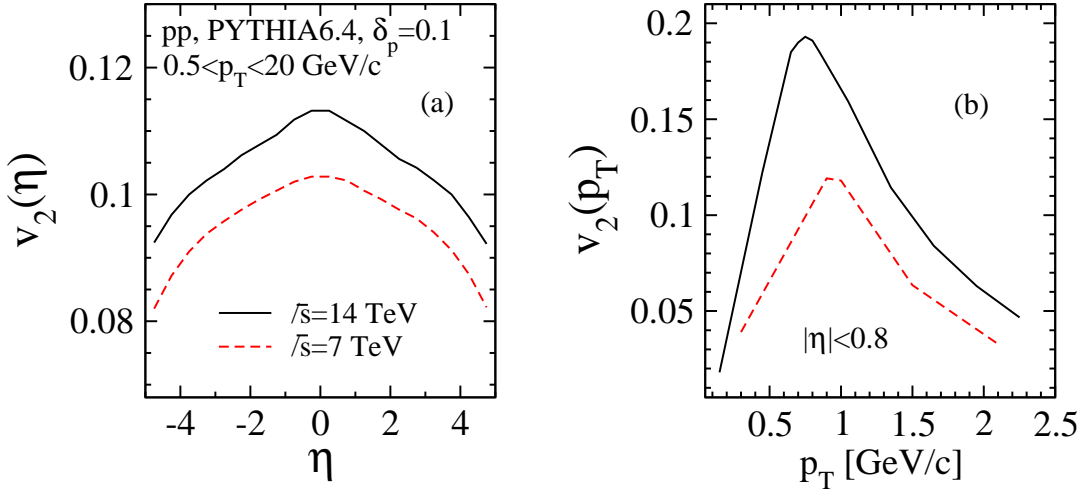


FIG. 2: (colour on line) (a) $v_2(\eta)$ and (b) $v_2(p_T)$ of charged particle calculated by modified PYTHIA6.4 with $\delta_p=0.1$ for the minimum bias pp collisions at $\sqrt{s}=7$ and 14 TeV, respectively.

ellipse with the half major and minor axes being respectively $p_T(1 + \delta_p)$ and $p_T(1 - \delta_p)$, instead of on a circle with radius p_T originally. The modified PYTHIA6.4 is then employed to calculate the charged particle transverse sphericity, ellipticity (eccentricity), and the elliptic flow parameter in the minimum bias pp collisions at $\sqrt{s}=0.9, 7$, and 14 TeV systematically. By fitting to the ALICE transverse sphericity data a suitable deformation parameter δ_p is obtained generally. With this δ_p the elliptic flow parameter as a function of η and p_T , $v_2(\eta)$ and $v_2(p_T)$, are predicted for the minimum bias pp collisions at $\sqrt{s}=7$ and 14 TeV. The v_2 upper limits, estimated at

the peak of the event-wise averaged $v_2(p_T)$ calculated in $|\eta| < 0.8$ with $\delta_p=0.1$, are 0.119 and 0.194 for the minimum bias pp collisions at $\sqrt{s}=7$ and 14 TeV, respectively. This theoretical prediction is consistent with the existed prediction of 0.04 - 0.2 [26-28].

We strongly suggest that the transverse momentum sphericity, ellipticity (eccentricity), and elliptic flow parameter are measured simultaneously, for the benefit of cross checking and reliable measurements. The theoretical way employed in this work, that is, fitting δ_p first to the measured charged particle transverse sphericity as a function of charged multiplicity and then employing the

fitted δ_p to study the elliptic flow and higher harmonics, may be applicable to other works.

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